INDUCTION BARRIER RF AND APPLICATIONS IN MAIN INJECTOR*

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Abstract

Two induction barrier rf systems have been designed and fabricated at Fermilab and installed in the Main Injector. They use the nanocrystal magnetic alloy called Finemet for the cavities and high voltage fast MOSFET switches for the modulators. Each system delivers ±10 kV square pulses at 90 kHz. They have been used for adiabatic beam stacking (beam compression), machine acceptance measurement and gap cleaning in the injection area for magnet protection, and will be tested for fast beam stacking for doubling the proton flux on the NuMI production target. The systems work reliably and cost much less than a resistive barrier rf system. Comparison with a similar system built at KEK reveals many similarities and also some important differences. This work is partially funded by the US-Japan collaborative agreement.

INTRODUCTION

The idea of an rf barrier was first suggested by J.E. Griffin et al. in 1983 [1]. It uses an isolated rf voltage wave (sinusoidal, rectangular or any other shape) to create a gap in a circular accelerator. As a first application, Griffin and his colleagues designed and built a barrier rf cavity for the Fermilab Antiproton Debuncher. It has two units, each consisting of a ceramic gap loaded with a 50 Ω resistor and surrounded by a shielding enclosure containing about 10 large MnZn ferrite rings. Each unit is 0.5 m in length and provides 450 V. This system has been working reliably and is still in use today.

In late '90s, BNL and KEK built another barrier rf system using resonant rf cavities [2]. The isolated rf voltage wave was created by reversing the rf current direction after one resonant period. This system could provide high voltage (several tens of kV). But the residual voltage oscillation was a serious problem even after compensation by a feedback system.

At about the same time, Fermilab purchased several wideband power supplies from Amplifier Research Co. to drive a resistor-loaded barrier rf system in the Recycler. This system works nicely but can only deliver 2 kV [3].

When the nanocrystal magnetic alloy Finemet was introduced by KEK for the rf system of the project J-PARC (former JHF), it was immediately realized that this low Q, high μ material could be an ideal candidate for a wideband barrier rf cavity. It could deliver much higher voltage than a resistor-loaded rf because of its high impedance (500-1000 Ω per cavity compared with 50 Ω). So the cost per volt would be much lower. Moreover, low quality factor ($Q < 1$) means this cavity is non-resonant. So the voltage oscillation problem experienced by the BNL system would be greatly suppressed. As a first attempt, a small Finemet cavity driven by a pulsed high voltage power supply was built and tested successfully. It was installed on the HIMAC linac as a chopper in 1998 and has been working well since then [4-7].

Encouraged by this success, two new induction barrier rf systems were built at Fermilab as part of the US-Japan collaboration on high intensity proton R&D. Each system consists of a Finemet cavity, a modulator and two impedance matching transformers. Each cavity is 0.5 m in length and delivers 10 kV. The first system has been in operation in the Main Injector since May 2005 and works reliably. The second system was installed in the Main Injector in April 2006.

The motivation to develop the induction barrier rf at Fermilab is to increase the proton intensity in the Main Injector. Presently the beam intensity in the Fermilab accelerator complex is limited by the Booster, which is a 30 years old machine and a bottleneck. Because the MI acceptance (about 0.7 eV-s, see below) is larger than the Booster beam emittance (about 0.13 eV-s), it is possible to stack two Booster bunches into one MI rf bucket. This will double the beam intensity in the MI. There are several ways for stacking. Barrier rf is one of them, which manipulates the beam in the longitudinal phase space. There are so-called "slow stacking" and "fast stacking." The former is simply adiabatic squeezing of the beam in the longitudinal direction. The latter is more complicated. It involves a debunching, reflecting and folding process and requires two barrier rf systems. It was first proposed by J.E. Griffin [8]. K-Y. Ng gave a detailed analysis in [9].

Barrier rf can also find other applications, for example, to generate a fat bunch for machine longitudinal acceptance measurement during transition crossing, and to generate a clean gap in the machine for magnet protection.

INDUCTION BARRIER RF

System layout

Figure 1 is a schematic drawing of an induction barrier rf system. The left part is upstairs in the rf gallery, and the right part in the Main Injector tunnel. Both are connected by 80-ft long 50 Ω cables. The high voltage solid state switches in the modulator must be far away from the machine in order to avoid possible radiation damage. To match the impedance of the cable (50 Ω) and the cavity (~500 Ω), two impedance matching transformers are used: one between the modulator and cable, another between the cable and the cavity. Measurement shows the reflected voltage wave is almost completely suppressed by this method.

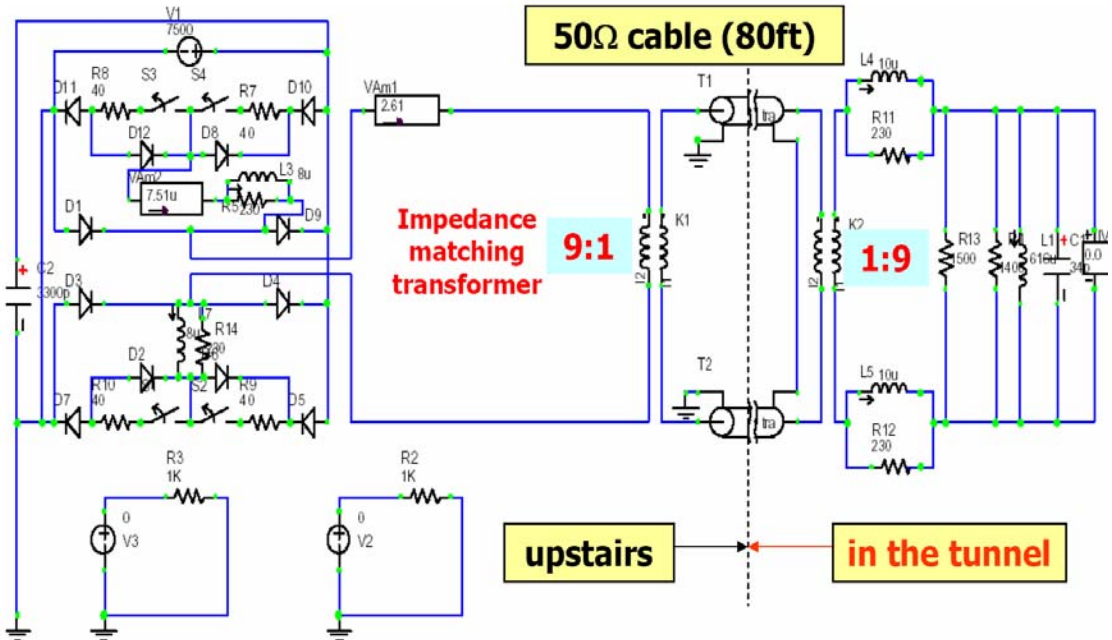

Figure 1: Schematic drawing of a barrier rf system. The left part is modulator in the rf gallery, the right part a cavity in the tunnel. Both are connected by 80-feet long cables and two impedance matching transformers.

Parameters and Components

Table 1 lists the parameters of this system. The cavities are shown in Figure 2, modulators in Figure 3. Each cavity contains seven Finemet cores made by Hitachi, Japan. Each modulator has a pair of bipolar high voltage fast MOSFET switches made by Behlke Co. in Germany.

Table 1: Barrier RF System Parameters

Pulsed peak accel. voltage	± 10 kV
Pulse length	0.4 μs
Pulse repetition rate	90 kHz
Burst length	400 ms
Burst repetition rate	0.5 Hz

Figure 2: Two barrier rf cavities and impedance matching transformers in the MI tunnel.

Figure 3: Two barrier rf modulators in MI-60 building.

Table 2 and 3 list the specifications of the MOSFET switches and Finemet cores.

Table 2: MOSFET Switch Specs

Type	HTS 161-06-GSM
Peak voltage	2 × 16 kV
Peak current	60 A
Pulse width	300 ns
Continuous switching frequency	90 kHz
Burst length	800 ms
Burst repetition rate	0.5 Hz
Cooling	Air / silicon oil

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Table 3: Finemet Core Specs

Type	FT3M
OD / ID	500 mm / 139.8 mm
Thickness	25 mm
Inductance	56 µH per core
Resistance	190 Ω per core

BENCH TEST

We compared the performance of the Finemet and ferrite 4M2 cores. The results are shown in Figure 4. It is seen that the Finemet can generate better square pulses than 4M2. This is because Finemet has higher permeability in the frequency range around MHz.

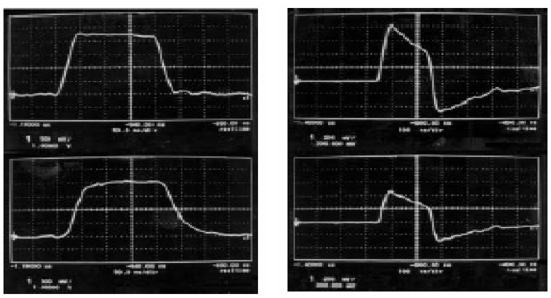

Figure 4: Left – Finemet core; right – 4M2 core. Upper curves are the primary voltage from the generator; lower curves the secondary voltage at the acceleration gap.

Significant efforts were made to tune the R, L, C parameters of the damper and snubber circuit in order to get a flat top and minimize the peak current and reflected voltage waves. One must pay special attention to the peak current. While the peak voltage is under one's control, the peak current is determined by the inductive load, the damper and snubber circuit. If it exceeds the specified value (60 A), the switch will be damaged permanently. Figure 5 shows the bench test results.

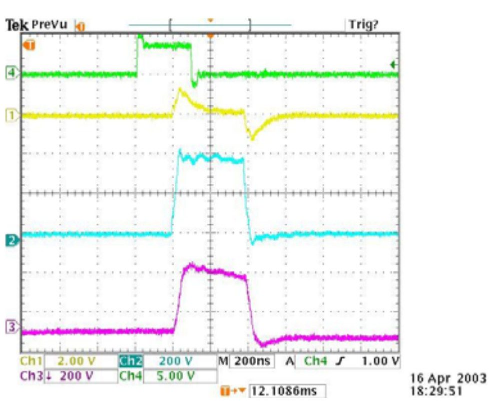

Figure 5: From top to bottom: trigger signal (green), current (yellow), primary voltage (light blue), secondary voltage at the gap (purple).

ADIABATIC STACKING

In this experiment, two consecutive Booster batches are injected into the Main Injector and captured by the 53 MHz rf buckets. Each batch has 84 bunches for a length of 1.6 µs. The two batches occupy a total length of 3.2 µs, which is 2/7 of the Main Injector circumference. The 53 MHz rf is then gradually turned off and the barrier rf turned on. So the beam is debunched and confined by the rf barriers. The barriers slowly move in to squeeze the beam to half of its original size, i.e., from 3.2 µs to 1.6 µs. Then the 53 MHz rf is on again to recapture the beam and start acceleration. Figure 6 is an illustration of this process. The beam is accelerated to 120 GeV with small losses.

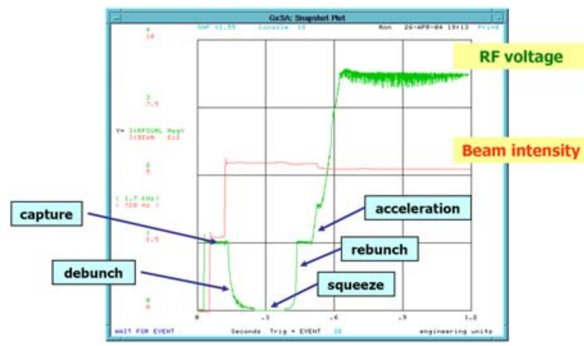

Figure 6: Adiabatic stacking process. The green curve is the 53 MHz rf voltage waveform. On the bottom of this curve, the barrier rf is on and moves to squeeze the beam.

Figure 7 is a dynamic plot of the barrier rf voltage and the beam. It shows how the barriers move in and the beam gets squeezed. Figure 8 is a mountain view picture of the beam in the Main Injector. It shows clearly that the beam is squeezed to about half of its original size after stacking.

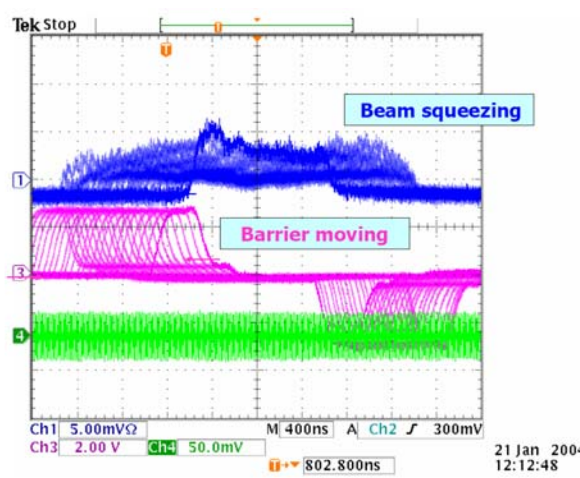

Figure 7: Dynamic plot showing the movement of the rf barrier and the beam. Note that the edge of the beam penetrates into the barrier.

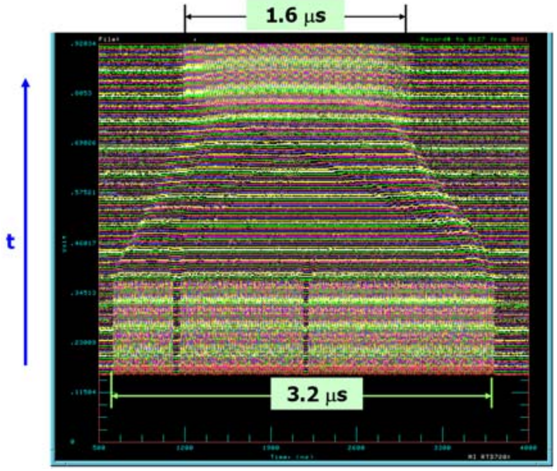

Figure 8: Mountain view picture of the beam. The beam size is reduced to half by the rf barrier.

INJECTION GAP CLEANING

The barrier rf is also used to clean up the gap between the slip-stacked batch and the NuMI batches. Due to mismatch between Booster bunch and slip stacking rf bucket, a considerable amount of beams (about 5-10%) are not captured during slip stacking and become dc beams, which move at a rate of $\eta \times \Delta p/p$ (slip factor times momentum spread) towards the unoccupied part of the machine. For a particle of an energy error of 15 MeV, the moving speed is about 1 μs (about 10% of the machine size) in one Booster cycle (67 ms). When a series of five NuMI batches are injected after slip stacking, these dc beams could spread to everywhere and be kicked to the downstream quads (Q104 and Q105) by injection kickers and cause high radiation activation. This problem can be avoided by using barrier rf to prevent the dc beams from leaking. Figure 9 is a comparison of the beam loss at Q104 with and without rf barrier. It is obvious that the gap when injecting the first 3 NuMI batches is much cleaner. However, the effect on the last 2 batches is minimal. This is due to the fact that the speed of the barrier move relative to the two edges of the slip stacked beam is different. Fast speed makes barrier confinement less effective.

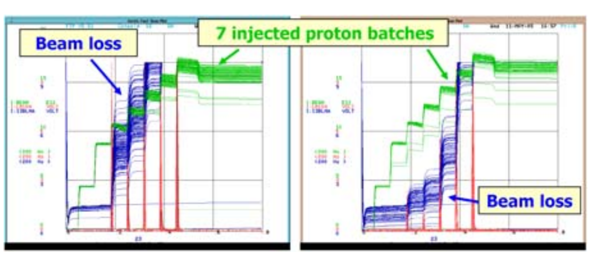

Figure 9: Seven Booster proton batches are injected into the MI. The first two are slip stacked for anti-proton production, the next five for neutrino production for the NuMI experiment. Red spikes are the instantaneous losses at Q104; blue ones the integrated loss. Left – without rf barrier; right – with rf barrier.

ACCEPTANCE MEASUREMENT

The barrier rf can readily create "fat" bunches. By using bunches with large longitudinal emittance, one can measure the machine acceptance. This is particularly useful in understanding the effect of transition crossing. Figure 10 shows the beam size at different beam intensities. The high intensity beam was created by the rf barrier.

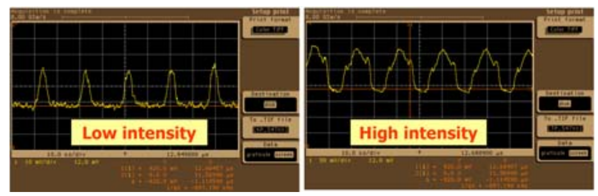

Figure 10: Proton bunch length in the 53 MHz rf bucket. The bunch almost occupies the entire bucket at high intensity.

The beam longitudinal emittance measurement during ramp can be done using the standard technique. Namely, from the synchronous phase and measured bunch length one can calculate the Hamiltonian ratio called parameter N, as shown in the left plot of Figure 11. Then from N and the synchronous phase one can find the area factor in the right plot of Figure 11. Multiplying the area factor by the stationary bucket area one gets the beam emittance. The result is 0.72 eV-s, which is more than 5 times as big as the normal beam emittance from the Booster, which is about 0.13 eV-s. Even at 0.72 eV-s, there wasn't any measurable beam loss during transition crossing. This means the machine acceptance is larger than 0.72 eV-s.

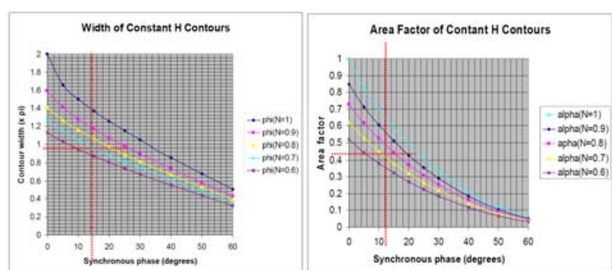

Figure 11: Plots for emittance measurement during ramp. Left – Hamiltonian ratio (parameter N) as a function of the synchronous phase and bunch length. Right – area factor (i.e., the ratio of the beam emittance to the stationary bucket area) as a function of synchronous phase and parameter N.

FAST STACKING

This method was reported in several published references [8-10]. Because it requires two barrier rf systems – one stationary, another moving – we could not test it until recently when the second system was installed in April 2006. The main advantage of this method is that the stacking will be continuous. The injected beam would have an energy offset. The beams would be reflected and folded by the barriers so that the earlier injected beams would be moved and repositioned on top of the later ones in the longitudinal phase space. Simulation shows the MI would be able to accept 12 Booster batches instead of 6 as it does now. So the intensity will be doubled. A key issue, however, is to keep the incoming Booster beam energy spread small (below ±10 MeV) after a bunch rotation. The experiment will start soon.

COMPARISON OF DIFFERENT BARRIER RF SYSTEMS

During this workshop, we made a comparison between several existing barrier rf systems. The results are summarized in Table 4.

On interesting result of this comparison is the big difference in cost per volt. While the resistive barrier rf system gives the best waveform (no residuals at all), it is also the most expensive one. This is because of its low impedance (50 Ω) compared to that of an inductive barrier rf cavity (500 – 1000 Ω). So for given output voltage the power requirement is higher. This explains an order of magnitude of differences in unit cost ($400/volt vs. $10/volt).

About 60% of the cost of an inductive barrier rf system comes from Finemet cores ($63k out of $100k for a 10 kV system built at Fermilab). Fortunately, we learned from a Hitachi representative at this workshop that Metglas Co. (which was purchased by Hitachi) will have a Finemet production line in South Carolina in the U.S. in a year or so. Therefore, the price would be cut by as much as 50%. Meanwhile, there are also new vendors entering this profitable market. For example, several companies in China have announced that they can produce Finemet-type materials. Although the quality of their products is yet to be tested, it is undoubtedly good news to the customers.

Another competition comes from a new product called Cobalt-based amorphous material. Its μQf value in the MHz frequency range is said to be comparable to or better than Finemet. Both Hitachi and Toshiba have this product. At this moment, it costs more than Finemet. However, the maximum size of a Finemet core is limited to OD ~ 1 m due to brittleness. Cobalt-based amorphous material has no size limit.

Table 4 shows that the KEK inductive barrier rf system costs more than that at Fermilab. There are several obvious reasons. For instance, the Fermilab system is made in house, whereas KEK uses contractors (industrial companies and university consultants). Also, the allowable power dissipation of the KEK system is higher and thus can be used for higher duty factor operation. However, some technical design difference also contributes to the cost difference. One is the impedance matching. The KEK system uses large matching resistor assembly in parallel to the cavity. These resistors consume lots of power from the generator. The Fermilab system uses matching transformers, which are small and consumes much less power. Another advantage of using matching transformers is that the standard 50 Ω cable can be used instead of the special 120 Ω cable required by the KEK system.

SUMMARY

Two barrier rf systems have been installed in the Fermilab Main Injector. One has been in operation since May 2003 and works reliably. It is used for beam stacking, magnet protection and machine acceptance measurement. Another was installed recently and will be used for fast stacking for the NuMI experiment.

A lot of experiences have been gained in the design and fabrication of induction barrier rf systems. In particular, the KEK and Fermilab systems have many similarities and yet some differences. Comparison of these systems is beneficial to both laboratories.

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Table 4: Comparison of Different Types of Barrier RF Systems

Type	Where	Application	Performance	Cost
Resonant (narrowband)	BNL AGS	Beam experiment (no longer in use)	Large residual wave High gradient (20 kV/m)	(unknown)
Resistive (wideband)	Fermilab Debuncher	Beam confinement	Reliable (since 1983) Low gradient (900 V/m)	(unknown)
	Fermilab Recycler	Momentum mining	Reliable (since 2003) Low gradient (600 V/m) Best waveform Low duty factor	High: $400/volt
Inductive (wideband)	Fermilab Main Injector	Longitudinal compression Fast beam stacking Magnet protection Acceptance measurement	Reliable (since 2005) High gradient (20 kV/m) Good waveform P(max) = 600 W per switch	Low: $10/volt
	KEK PS	Longitudinal focusing	High gradient (10 kV/m) Good waveform P(max) = 1400 W per arm	Medium: $60-70/volt